

PROCESSING ONE-LOOP VIRTUAL CORRECTIONS WITH SAMURAI

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LoopFest IX

Radiative Corrections for the LHC and Lepton Colliders

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Collaboration with: **P. Mastrolia, T. Reiter, F. Tramontano**

CREDITS

Work developed in collaboration with:

Pierpaolo Mastrolia, Thomas Reiter, Francesco Tramontano

SAMURAI

Scattering **AMplitudes** from **Unitarity-based**
Reduction **Algorithm** at the **Integrand-level**

e-Print: arXiv:1006.0710 [hep-ph]



ONE-LOOP MULTI-LEG STATE-OF-THE-ART

Several $2 \rightarrow 4$ processes have been completed:

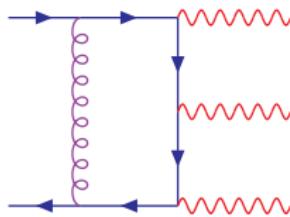
- $pp \rightarrow W + 3 \text{ jets}$
Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre
Ellis, Melnikov, Zanderighi
- $pp \rightarrow t\bar{t} b\bar{b}$
Bredenstein, Denner, Dittmaier, Pozzorini
Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
- $pp \rightarrow t\bar{t} + 2 \text{ jets}$
Bevilacqua, Czakon, Papadopoulos, Worek
- $pp \rightarrow Z + 3 \text{ jets}$
Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre

Many different approaches have been used!

What is SAMURAI?

- OPP reduction algorithm
G.O., Papadopoulos, Pittau (2007)
- d-dimensional extension
Ellis, Giele, Kunszt, Melnikov (2008)
- coefficients of polynomials via DFT
Mastrolia, G.O., Papadopoulos, Pittau (2008)
- automated generation of numerators
 - processes of high complexity (EW): less diagrams/more scales
 - processes of high multiplicity (QCD): more diagrams/less scales

ONE-LOOP – DEFINITIONS



Any m -point one-loop amplitude can be written, before integration, as

$$A(\bar{q}) = \frac{N(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

where

$$\bar{D}_i = (\bar{q} + p_i)^2 - m_i^2 \quad , \quad \bar{q}^2 = q^2 - \mu^2 \quad , \quad \bar{D}_i = D_i - \mu^2$$

Our task is to calculate, for each phase space point:

$$\mathcal{M} = \int d^d \bar{q} \ A(\bar{q}) = \int d^d \bar{q} \frac{N(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

“STANDING ON THE SHOULDERS OF GIANTS”

1 Passarino-Veltman Reduction to Scalar Integrals

$$\begin{aligned}\mathcal{M} = & \sum_i \textcolor{blue}{d}_i \text{ Box}_i + \sum_i \textcolor{blue}{c}_i \text{ Triangle}_i \\ & + \sum_i \textcolor{blue}{b}_i \text{ Bubble}_i + \sum_i \textcolor{blue}{a}_i \text{ Tadpole}_i + \mathbf{R},\end{aligned}$$

- Set the basis for our NLO calculations
- Exploits the Lorentz structure

2 Pittau/del Aguila Recursive Tensorial Reduction

- Express $q^\mu = \sum_i \textcolor{violet}{G}_i \ell_i^\mu$, $\ell_i^2 = 0$
- The generated terms might reconstruct denominators D_i or vanish upon integration

3 “Cut-based” Techniques (Bern, Dixon, Dunbar, Kosower in '94) direct extraction of the coefficients of the scalar integral

Pigmaei gigantum humeris impositi plusquam ipsi gigantes vident

THE TRADITIONAL “MASTER” FORMULA

$$\begin{aligned}\int A &= \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} d(i_0 i_1 i_2 i_3) D_0(i_0 i_1 i_2 i_3) \\ &+ \sum_{i_0 < i_1 < i_2}^{m-1} c(i_0 i_1 i_2) C_0(i_0 i_1 i_2) \\ &+ \sum_{i_0 < i_1}^{m-1} b(i_0 i_1) B_0(i_0 i_1) \\ &+ \sum_{i_0}^{m-1} a(i_0) A_0(i_0) \\ &+ \text{rational terms}\end{aligned}$$

OPP “MASTER” FORMULA - I

4-dim identity at the integrand level for $N(q)$ in terms of **4-dim** D_i

$$\begin{aligned} N(q) &= \sum_{i_0 < i_1 < i_2 < i_3}^{m-1} \left[d(i_0 i_1 i_2 i_3) + \tilde{d}(q; i_0 i_1 i_2 i_3) \right] \prod_{i \neq i_0, i_1, i_2, i_3}^{m-1} D_i \\ &+ \sum_{i_0 < i_1 < i_2}^{m-1} \left[c(i_0 i_1 i_2) + \tilde{c}(q; i_0 i_1 i_2) \right] \prod_{i \neq i_0, i_1, i_2}^{m-1} D_i \\ &+ \sum_{i_0 < i_1}^{m-1} \left[b(i_0 i_1) + \tilde{b}(q; i_0 i_1) \right] \prod_{i \neq i_0, i_1}^{m-1} D_i \\ &+ \sum_{i_0}^{m-1} \left[a(i_0) + \tilde{a}(q; i_0) \right] \prod_{i \neq i_0}^{m-1} D_i \end{aligned}$$

$\tilde{d}(q), \tilde{c}(q), \tilde{b}(q), \tilde{a}(q)$ are “spurious” terms that vanish upon integration

IMPORTANT POINTS

G.O., Papadopoulos, Pittau (2007)

- 1 The **functional form** of the OPP master formula is **universal** (**process independent**)
- 2 The **only information required** in order to extract the coefficients of the master integrals is the knowledge of **the numerical value of the numerator function for a finite set of values $\{q_i\}$ of the integration momentum**
- 3 The process becomes particularly simple if we **choose** $\{q_i\}$ such that sets of **denominators D_i vanish** ("cuts")

OPP “MASTER” FORMULA - II

4-dim identity at the integrand level for $N(q)$ in terms of **4-dim** D_i

$$\begin{aligned} N(q) &= \sum_{i << \ell}^{n-1} \Delta_{ijk\ell}(q) \prod_{h \neq i,j,k,\ell}^{n-1} D_h + \sum_{i << k}^{n-1} \Delta_{ijk}(q) \prod_{h \neq i,j,k}^{n-1} D_h \\ &+ \sum_{i < j}^{n-1} \Delta_{ij}(q) \prod_{h \neq i,j}^{n-1} D_h + \sum_i^{n-1} \Delta_i(q) \prod_{h \neq i}^{n-1} D_h \end{aligned}$$

where:

$$\Delta_{ijk\ell}(q) = c_{4,0}^{(ijkl)} + c_{4,1}^{(ijkl)} \tilde{F}(q)$$

and so on for triangles, bubbles, and tadpoles.

IDENTITY IN D-DIMENSIONS: $q \rightarrow \bar{q}$

Ellis, Giele, Kunszt, Melnikov (2008)
Melnikov, Schulze (2010)

$$\begin{aligned} N(\bar{q}) &= \sum_{i << m}^{n-1} \Delta_{ijklm}(\bar{q}) \prod_{h \neq i,j,k,\ell,m}^{n-1} \bar{D}_h + \sum_{i << \ell}^{n-1} \Delta_{ijkl}(\bar{q}) \prod_{h \neq i,j,k,\ell}^{n-1} \bar{D}_h + \\ &+ \sum_{i << k}^{n-1} \Delta_{ijk}(\bar{q}) \prod_{h \neq i,j,k}^{n-1} \bar{D}_h + \sum_{i < j}^{n-1} \Delta_{ij}(\bar{q}) \prod_{h \neq i,j}^{n-1} \bar{D}_h + \sum_i^{n-1} \Delta_i(\bar{q}) \prod_{h \neq i}^{n-1} \bar{D}_h \end{aligned}$$

- 1 Add a spurious pentagon term in μ^2

$$\Delta_{ijklm}(\bar{q}) = c_{5,0}^{(ijklm)} \mu^2$$

- 2 The coefficients have a more complicated structure

$$\Delta_{ijkl}(\bar{q}) = c_{4,0} + c_{4,2} \mu^2 + c_{4,4} \mu^4 + (c_{4,1} + c_{4,3} \mu^2) \tilde{F}(q)$$

MASTER INTEGRALS

The blue coefficients, such as $c_{4,0}$ or $c_{4,4}$ multiply non-vanishing integrals:

$$\int d^d \bar{q} A(\bar{q}) = c_{4,0} \int d^d \bar{q} \frac{1}{\bar{D}_i \bar{D}_j \bar{D}_k \bar{D}_\ell} + c_{4,4} \int d^d \bar{q} \frac{\mu^4}{\bar{D}_i \bar{D}_j \bar{D}_k \bar{D}_\ell} + \dots$$

In addition to the standard **scalar integrals**

QCDloop (Ellis, Zanderighi)
OneLoop (van Hameren)

we need the following additional integrals

$$\int d^d \bar{q} \frac{\mu^2}{\bar{D}_i \bar{D}_j} , \quad \int d^d \bar{q} \frac{\mu^2}{\bar{D}_i \bar{D}_j \bar{D}_k} , \quad \int d^d \bar{q} \frac{\mu^4}{\bar{D}_i \bar{D}_j \bar{D}_k \bar{D}_l}$$

EXTRACTING THE COEFFICIENTS VIA DFT

Mastrolia, G.O., Papadopoulos, Pittau (2008)

The coefficients can be extracted by means of *projections*, by exploiting:

- polynomial structure of the integrand $P(x) = \sum_{\ell=0}^n c_\ell x^\ell$
 - freedom in choosing the solutions for the cuts
- 1 generate the set of discrete values P_k ($k = 0, \dots, n$),

$$P_k = P(x_k) = \sum_{\ell=0}^n c_\ell \rho^\ell e^{-2\pi i \frac{k}{(n+1)} \ell},$$

by sampling $P(x)$ at the points $x_k = \rho e^{-2\pi i \frac{k}{(n+1)}}$;

- 2 using the orthogonality relation each coefficient c_ℓ reads,

$$c_\ell = \frac{\rho^{-\ell}}{n+1} \sum_{k=0}^n P_k e^{2\pi i \frac{k}{(n+1)} \ell}$$

NUMERATOR FUNCTIONS

According to the chosen dimensional regularization scheme the numerator can be written as:

$$\mathcal{N}(\bar{q}, \epsilon) = N_0(\bar{q}) + \epsilon N_1(\bar{q}) + \epsilon^2 N_2(\bar{q})$$

N_0 , N_1 and N_2 , are functions of q^ν and μ^2

Rational Terms:

- the term proportional to μ^2 is **automatically included** in the reduction of N_0 .
- the term proportional to ϵ , **if present**, can be reduced using the same algorithm on N_1

SAMURAI can reduce integrands defined in two ways

- *numerator functions* (sitting on products of denominators)
- *products of tree-level amplitudes* (sewn along cut-lines)

GENERAL FEATURES OF SAMURAI

SAMURAI is a **fortran90 library** for the calculation of the virtual one-loop corrections

- It is **publicly available** at www.cern.ch/samurai
- The main purpose was to provide a **flexible and user-friendly tool** for the evaluation of the virtual corrections
- It works with any number/kind of legs
- It can process integrands written either as numerator of Feynman diagrams or as product of tree level amplitudes
- It is interfaced with **QCDDloop** and **OneLOop** for the evaluation of scalar integrals
- It has a modular structure that allows for **quick local updates**
- It is easy to **interface with other existing tools**

RUNNING SAMURAI

The sequence of commands is the following:

```
call initsamurai(imeth,isca,verbosity,itest)
call InitDenominators(nleg,Pi,msq,v0,m0,v1,m1,...,vlast,mlast)
call samurai(xnum,tot,totr,Pi,msq,nleg,rank,istop,scale2,ok)
call exitsamurai
```

A dedicated module (kinematic) contains useful functions to evaluate:

- Polarization vectors for massless vectors
- Scalar and spinor products with both real and complex four vectors as arguments

```
call initSamurai(imeth,isca,verbosity,itest)
```

- **imeth** – style of the numerator
 - = 'diag' for an integrand given as numerator of Feynman diagrams
 - = 'tree' for an integrand given as products of tree-level amplitudes
- **isca** – routines for scalar integrals
 - = 1 QCDLoop ([Ellis, Zanderighi](#))
 - = 2 OneLoop ([van Hameren](#))
- **verbosity** – level of information in the output
 - = 0 no output from the library
 - = 1 all coefficients are printed
 - = 2 value of the integrals
 - = 3 the outcome of the numerical test
- **itest** – test on the quality of the numerical reconstruction
 - = 0 no test
 - = 1 global ($N = N$)-test
 - = 2 local ($N = N$)-test
 - = 3 power-test

CALL SAMURAI

```
call samurai(xnum,tot,totr,Pi,msq,nleg,rank,istop,scale2,ok)
```

- **xnum** - [i] Numerator function in the form `xnum(cut,q,mu2)`
- **tot** - [o] The complex variable `tot` contains the final result for the integrated amplitude of numerator `xnum`. The finite part, that also includes the rational term, the single and double poles.
- **totr** - [o] For the purpose of comparisons and debugging, we also provide the rational part `totr` alone.
- **nleg** - [i] Number of denominators
- **Pi** - [i] Internal momenta $\bar{D}_i = (\bar{q} + \text{Pi})^2 - \text{msq}$
- **msq** - [i] Internal masses
- **rank** - [i] This integer value is the maximum rank of the numerator.
- **istop** - [i] This flag stops the reduction at the level requested by the user.
- **scale2** - [i] This is the scale (squared) used for the scalar integrals.
- **ok** - [o] Outcome of the test: the default values is `ok=true`, and it is set to `ok=false` when the reconstruction test fails.

PRECISION TESTS

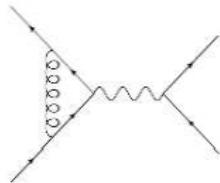
We use again the decomposition of $N(\bar{q})$ after determining all coefficients

$$\begin{aligned} N(\bar{q}) &= \sum_{i << m}^{n-1} \Delta_{ijklm}(\bar{q}) \prod_{h \neq i,j,k,\ell,m}^{n-1} \bar{D}_h + \sum_{i << \ell}^{n-1} \Delta_{ijk\ell}(\bar{q}) \prod_{h \neq i,j,k,\ell}^{n-1} \bar{D}_h + \\ &+ \sum_{i << k}^{n-1} \Delta_{ijk}(\bar{q}) \prod_{h \neq i,j,k}^{n-1} \bar{D}_h + \sum_{i < j}^{n-1} \Delta_{ij}(\bar{q}) \prod_{h \neq i,j}^{n-1} \bar{D}_h + \sum_i^{n-1} \Delta_i(\bar{q}) \prod_{h \neq i}^{n-1} \bar{D}_h \end{aligned}$$

- 1 Global ($N = N$)-test
- 2 Local ($N = N$)-test
- 3 Power-test

EXAMPLE: $u\bar{u} \rightarrow e^+e^-$

easy example of a numerator with ϵ -dependent term



If one want to consider regularization schemes giving rise to $O(\epsilon)$ terms and reduce them, then one needs to process N_0 and N_1 below separately

$$\mathcal{N}(\bar{q}, \epsilon) = N_0(\bar{q}) + \epsilon N_1(\bar{q}) + \epsilon^2 N_2(\bar{q}).$$

- imeth = 'diag'
- nleg = 3, rank = 2

$d=4 \rightarrow$ Dim Red
 $d=4-2\epsilon \rightarrow$ CDR



$$N(q, \mu^2) = C_F g_s^2 e^2 \bar{u}(p_{e^-}) \gamma^\mu v(p_{e^+}) \bar{v}(p_{\bar{u}}) [2(2-d) \bar{q}^\mu \not{q} + [(d-2) \bar{q}^2 + 4(p_u \cdot \bar{q} - p_{\bar{u}} \cdot \bar{q} - p_u \cdot p_{\bar{u}})] \gamma^\mu] u(p_u)$$

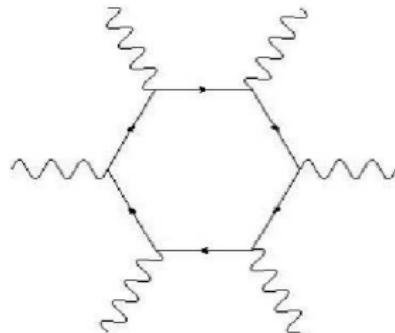
Denominators: $\bar{q}^2 \quad (\bar{q} + p_u)^2 \quad (\bar{q} + p_u + p_{e^-} + p_{e^+})^2$

- msq = { 0, 0, 0 }
- Pi = { 0, p_u , $p_u + p_{e^-} + p_{e^+}$ }
- N_1 generate a rational term = $-g_s^2 C_F L0$

EXAMPLE: 6-PHOTON AMPLITUDES

6-photons

- imeth = 'diag'
- nleg = 6, rank = 6
- 120 permutations, only 60 relevant



$$N(q, \mu^2) = N(q) = -\text{Tr} [L_1 \not{\epsilon}_2 L_2 \not{\epsilon}_3 L_3 \not{\epsilon}_4 L_4 \not{\epsilon}_5 L_5 \not{\epsilon}_6 L_6 \not{\epsilon}_1].$$

Bernicot et al (2007, 2008)

$$\frac{s}{\alpha^3} A(-, -, +, +, +, +) = 11075.04009210435 ,$$
$$\frac{s}{\alpha^3} A(+, -, -, +, +, -) = 7814.762085902767 ,$$

SAMURAI with istop=2

$$\frac{s}{\alpha^3} A(-, -, +, +, +, +) = \underline{11075.040174990} ,$$
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PS point as in Nagy and Soper (2006)

$$\vec{p}_3 = (33.5, 15.9, 25.0)$$

$$\vec{p}_4 = (-12.5, 15.3, 0.3)$$

$$\vec{p}_5 = (-10.0, -18.0, -3.3)$$

$$\vec{p}_6 = (-11.0, -13.2, -22.0)$$

SAMURAI with istop=3, subtracting totr

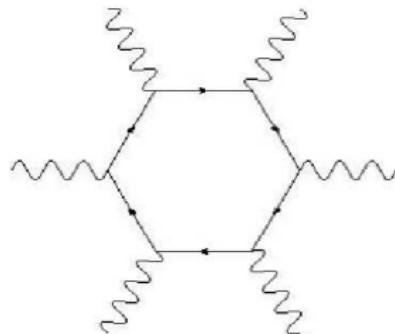
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Results numerically checked vs. Bernicot et al (2007, 2008)

See also: Mahlon (1994), Binotto et al. (2007), OPP (2007)

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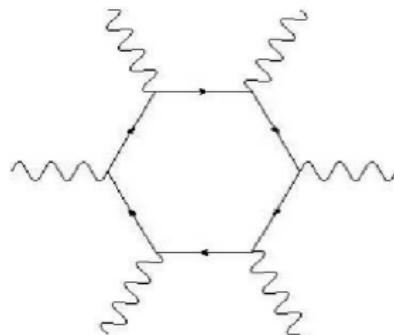
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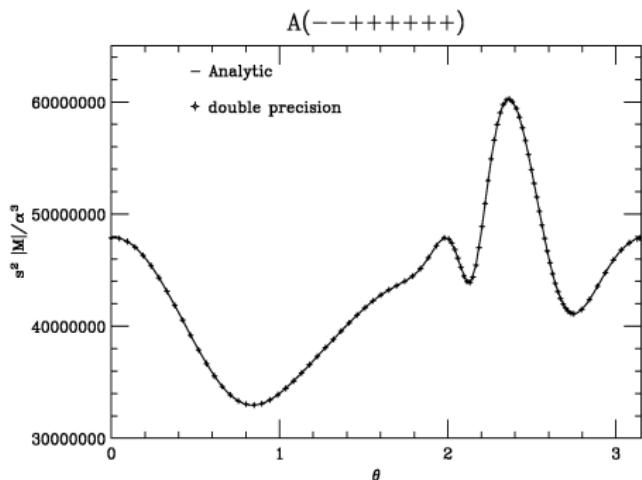
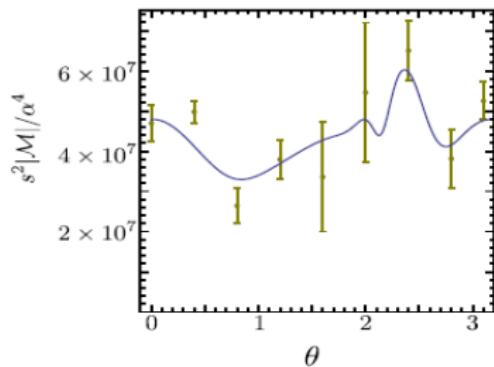
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Results numerically checked vs. Bernicot et al (2007, 2008)

See also: Mahlon (1994), Binotto et al. (2007), OPP (2007)

EXAMPLE: 8-PHOTON AMPLITUDES

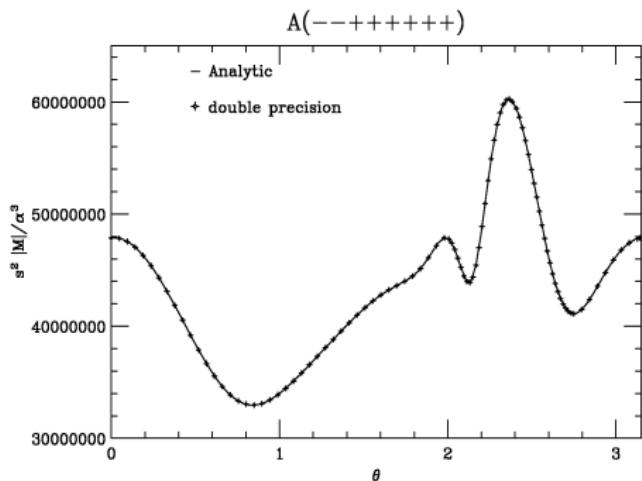
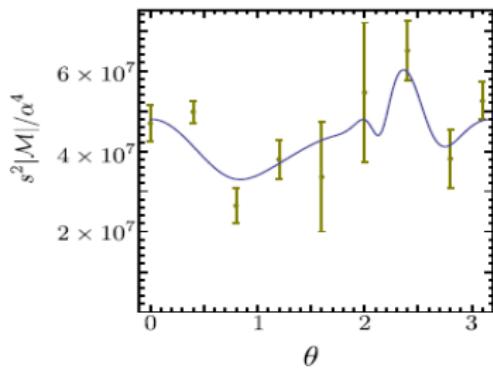
- imeth =diag
- nleg = 8, rank = 8
- 5040 permutations, only 2520 relevant
- sampling set as in Gong et al (2008)



Mahlon (1994), Gong, Nagy, Soper (2008)

EXAMPLE: 8-PHOTON AMPLITUDES

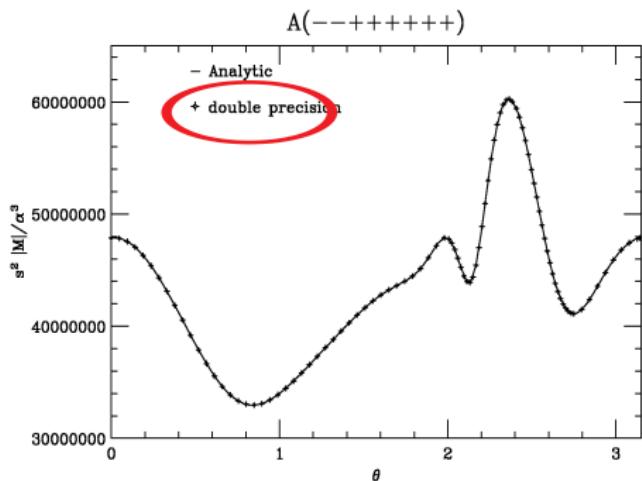
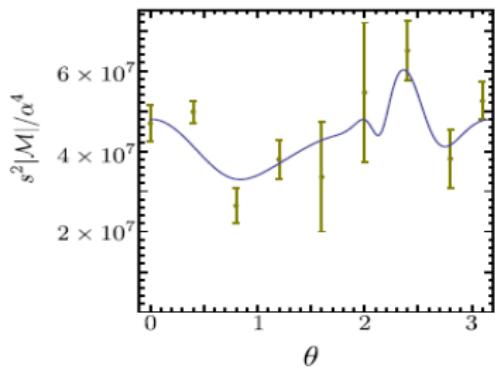
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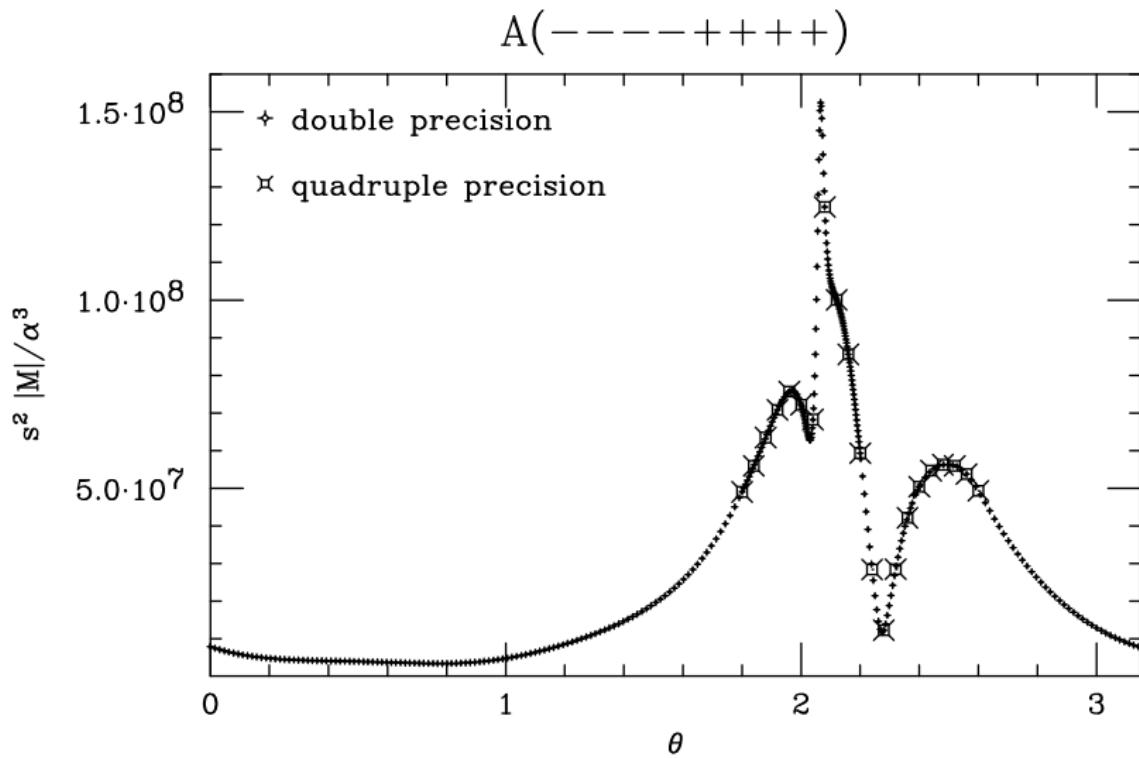
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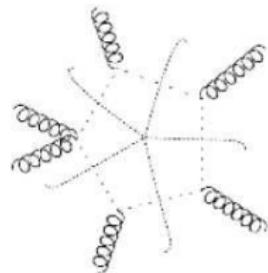
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EXAMPLE: 8-PHOTON AMPLITUDES



6-GLUONS

6-gluons all plus: *massive scalar contribution*



$$A_3^{\text{tree}}(1_s; 2^+; 3_s) = \frac{[2|1|r_2]}{\langle 2 r_2 \rangle}, \quad \text{imeth='tree'}$$
$$A_4^{\text{tree}}(1_s; 2^+, 3^+; 4_s) = \frac{\mu^2 [2|3]}{\langle 2 3 \rangle (p_{12}^2 - \mu^2)},$$
$$A_5^{\text{tree}}(1_s; 2^+, 3^+, 4^+; 5_s) = \frac{\mu^2 [2|1 (2+3)|4]}{\langle 2 3 \rangle \langle 3 4 \rangle (p_{12}^2 - \mu^2)(p_{45}^2 - \mu^2)},$$

$$N(q, \mu^2) = A_4(L_1; 1^+, 2^+; -L_2) \times A_3(L_2; 3^+; -L_3) \times A_3(L_3; 4^+; -L_4) \\ \times A_3(L_4; 5^+; -L_5) \times A_3(L_5; 6^+; -L_1)$$

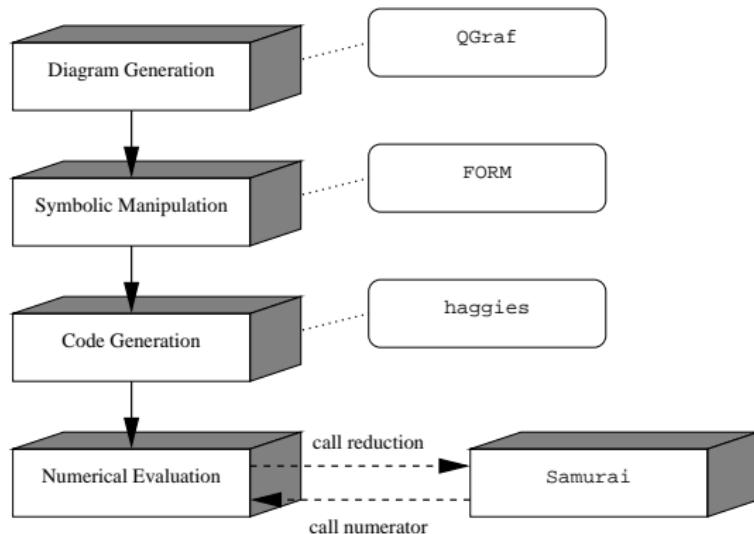
For this helicity choice the result is purely rational

Results numerically checked vs. Badger et al (2005)

AUTOMATION

An **automated generation** of the input files becomes **necessary** as the complexity of the process increases.

We have an automated setup using QGraf, FORM and haggies.



6-QUARKS

- The amplitude for $q_1\bar{q}_1 \rightarrow q_2\bar{q}_2 q_3\bar{q}_3$ involves **258 Feynman diagrams** (8 hexagons, 24 pentagons, 42 boxes, 70 triangles, and 114 bubbles)
- All Feynman diagrams contributing to the process are **automatically written in Fortran90 files** fully compatible with the reduction library
- In order to check our algebraic manipulations, we also compute the part of the numerator proportional to ϵ .
- The **generation of the code for the full process takes less than 10 minutes**, and the result for each helicity amplitude is produced in about **55 ms per phase-space point**

The results of SAMURAI and golem95 are in agreement

Application to **4b production**
– see talk of Nicolas Greiner –

CONCLUSIONS

Scattering AMplitudes from Unitarity-based
Reduction Algorithm at the Integrand-level

P. Mastrolia, G. O., T. Reiter, F. Tramontano
e-Print: arXiv:1006.0710 [hep-ph]

- SAMURAI is a new library for the automated evaluation of the NLO virtual corrections
- Modular , User-friendly , Publicly Available

<http://cern.ch/samurai>

- Ready to be interfaced with other tools (and tested!)
- Next Step: Physics and Improvements